

Previous Investigations and Reports

Various proposed Sites and Colusa Reservoir Projects have been evaluated over the past 40 years. In 1957 a 48,000 acre-foot reservoir was proposed by the California Department of Water Resources on Stone Corral and Funks Creeks as part of Bulletin No. 3, *The California Water Plan 1957* (DWR 1957). The Tehama-Colusa Canal would supply water to users. This project was again proposed by DWR in 1964 in Bulletin 109, *Colusa Basin Investigation* (DWR 1964), as part of flood control measures on Stone Corral and Funks Creeks.

The U.S. Bureau of Reclamation first considered larger projects at the Sites location in 1964 as part of its *West Sacramento Canal Unit Report* (DOI-USBR 1964). Fieldwork for this report included core drilling of the abutments and bucket augering in the channels at or near DWR's proposed Sites and Golden Gate Dam sites. In 1969 USBR identified four potential borrow areas for impervious materials within Sites Reservoir and three potential areas for riprap, rockfill, or bedding materials outside of the reservoir area. Twenty-five bucket auger holes were drilled and two stream-cut sample trenches were excavated to evaluate potential sources of impervious earth materials.

In 1980 USBR reanalyzed the project area and examined a larger Sites Reservoir design with a capacity of 1.8 maf. This proposal has become the basis for the Sites Reservoir Project evaluated in this investigation.

Additional proposals for the Sites Reservoir since 1980 have been mentioned in various USBR and DWR reports. These include:

- *Enlarging Shasta Lake Feasibility Study - Descriptions of Alternative Storage Facilities* (DOI-USBR 1982)
- *Enlarging Shasta Lake Feasibility - Progress Report* (DOI-USBR 1983a)
- *Assessment of Bureau of Reclamation Planning Activities Involving New Water Supplies* (DOI-USBR 1983)
- *Least-Cost CVP Yield Increase Plan - Appendix 6, Surface Storage and Conveyance* (DOI-USBR 1995)
- *California Water Plan Update*, Bulletin 160-93 (DWR 1993)

In 1990 the engineering consulting firm CH2M Hill prepared a long-range plan for the Glenn-Colusa Irrigation District that included an 870,000 acre-foot configuration of Sites Reservoir based on the 1964 USBR report. CH2M Hill followed this with the more general 1993 report *Meeting California's Water Needs in the 21st Century*.

Project Description

The proposed Sites and Colusa Reservoir Projects are on the west side of the Sacramento Valley, roughly halfway between Sacramento and Red Bluff (Figures 1 and 2). Three reservoir configurations are under consideration by DWR: a 1.2 million acre-foot smaller Sites Reservoir, a 1.8 maf larger Sites Reservoir, and a 3.1 maf Colusa Reservoir that includes the Colusa Cell to the north. Both the smaller and larger Sites configurations would have two main dams: Sites Dam on Stone Corral Creek and Golden Gate Dam on Funks Creek. The larger Sites Dam has a proposed height of 277 feet with a crest elevation of 540 feet. It would be an embankment structure requiring 4,694,00 yd³ of construction materials. Golden Gate Dam has a proposed height of 310 feet with a crest elevation of 540 feet. It would be an embankment structure with a volume of 11,262,000 yds³. The Golden Gate outlet works would be located just south of Golden Gate Dam. Its components would include a 30-foot diameter inlet-outlet tunnel extending for 3,300 feet, a penstock extending about 875 feet, and an access shaft for the tunnel gates that would extend 400 feet from the ridge top to tunnel invert.

An additional nine saddle dams would be placed along the northern rim of the reservoir, with some of these almost as large as the main dams. The water would be conveyed via the Tehama-Colusa Canal, Glenn-Colusa Canal, and/or possibly a new cross-valley canal to the existing Funks Reservoir. Water would then be pumped into the proposed reservoir via the Golden Gate inlet-outlet works.

The larger Colusa facility would extend into the northern Colusa and Glenn Counties. The additional facilities would include Hunters Dam on Hunters Creek, Logan Dam on Logan Creek, and at least five saddle dams along the far northern rim. Some of these proposed saddle dams are almost as large as the major dams. Water would be pumped into this proposed reservoir via the Golden Gate inlet-outlet works.

This investigation concentrated on evaluating Sites and Golden Gate Dam sites as part of the Sites Reservoir Projects. However, the Owens component of the Hunters Dam site was included in anticipation of the future evaluation of the larger Colusa Reservoir Project.

Project Chronology

Drilling began on May 11, 1998, with angle drill hole LC-2 on the left channel at the Sites Dam site. It ended about 15 months later on August 6, 1999, with the demobilization of the last drill rig off of auger hole AUG-3 at saddle dam site number 3 at the northern Sites saddle dam alignment (Table 1). Four angle holes ranging in depth from 130 to 250 feet were drilled in the channel at Sites Dam site to explore for the presence of faults. The abutments at Sites were not drilled because USBR drilled them in 1979 and 1980. Three vertical holes were

drilled near the axis of the proposed straight downstream Golden Gate Dam site and an angle hole drilled to explore a fault. Three vertical holes were placed along the axis of the Owens component of the proposed Hunters Dam site, and a single angle hole placed to intersect a fault as mapped. Five vertical holes were drilled at the Golden Gate inlet-outlet works to explore the foundation conditions of the proposed pumping plant, portals of the tunnel alignment, and each of the proposed spillways. Two angle holes and one vertical hole were drilled at 2 of the 12 proposed saddle dam sites along the Sites northern saddle dam alignment. Sixteen auger holes were augered at these six sites to evaluate alluvial materials in the channel, depths to bedrock, and stripping estimates, and to monitor groundwater levels.

Table 1. DWR drilling footage of the Sites and Colusa Reservoir Projects

Drill Site	Drill Hole	Date Started	Date Completed	Drill Footage
Sites Dam Site	LC-2	May 11, 1998	May 20, 1998	202.2
	LC-1	May 22, 1998	May 28, 1998	140.6
	LC-3	Jun 01, 1998	Jun 05, 1998	198.0
	LC-4	Jun 10, 1998	Jun 16, 1998	199.6
Total HQ Diamond Drill Footage				740.4
Sites Dam Site	SS-AUG-1	May 21, 1998	May 21, 1998	10.5
	SS-AUG-2	May 22, 1998	May 22, 1998	16.9
	SS-AUG-3	May 22, 1998	May 22, 1998	14.0
Total Auger Footage				41.4
Total Footage				<u>781.8</u>
Golden Gate Dam Site	RC-1	Jun 22, 1998	Jun 28, 1998	134.6
	LC-1	Jun 29, 1998	Jul 06, 1998	203.7
	LA-1	Jul 08, 1998	Jul 15, 1998	248.8
	RA-1	Jul 21, 1998	Jul 24, 1998	<u>249.2</u>
Total HQ Diamond Drill Footage				836.3
Golden Gate Dam Site	GG-AUG-4	Jun 26, 1998	Jun 26, 1998	21.0
	GG-AUG-5	Jul 31, 1998	Jul 31, 1998	18.7
	GG-AUG-6	Jul 31, 1998	Jul 31, 1998	<u>28.0</u>
Total Auger Footage				67.7
Total Footage				<u>904.0</u>
Golden Gate Outlet Works	DHPP-1	Jun 22, 1999	Jun 24, 1999	199.6
	DHPP-1B	Jun 26, 1999	Jun 26, 1999	20.3
	DHT-1	Jun 26, 1999	Jul 01, 1999	224.5
	DHT-4	Jul 01, 1999	Jul 10, 1999	199.5
	DHS-4	Jul 10, 1999	Jul 13, 1999	199.5
	DHS-1	Jul 13, 1999	Jul 20, 1999	<u>199.0</u>
Total HQ Diamond Drill Footage				1,042.4

Drill Site	Drill Hole	Date Started	Date Completed	Drill Footage
Golden Gate Outlet Works	GGO-AUG-3	Jun 26, 1999	Jun 26, 1999	36.3
	GGO-AUG-5	Jun 30, 1999	Jun 30, 1999	13.4
	GGO-AUG-6	Jun 30, 1999	Jun 30, 1999	19.0
	GGO-AUG-7	Jun 30, 1999	Jun 30, 1999	5.9
	GGO-AUG-2	Jul 01, 1999	Jul 01, 1999	13.5
	GGO-AUG-4	Jul 13, 1999	Jul 13, 1999	13.9
	GGO-AUG-1	Jul 22, 1999	Jul 22, 1999	<u>11.0</u>
Total Auger Footage				113.0
Total Footage				<u>1,155.4</u>
Northern Saddle Dam Alignment	SSD3-1	Jul 27, 1999	Jul 29, 1999	160.5
	SSD3-2	Jul 29, 1999	Aug 04, 1999	265.0
	SSD6-1	Aug 02, 1999	Aug 04, 1999	<u>119.0</u>
Total HQ Diamond Drill Footage				544.5
Northern Saddle Dam Alignment	SSD3-AUG-1	Aug 04, 1999	Aug 04, 1999	14.0
	SSD3-AUG-2	Aug 04, 1999	Aug 04, 1999	9.0
	SSD3-AUG-3	Aug 04, 1999	Aug 04, 1999	<u>21.5</u>
Total Auger Footage				44.5
Total Footage				<u>589.0</u>
Hunters Dam Site (Owens) Component)	LC-1	Aug 03, 1998	Aug 06, 1998	203.3
	RC-1	Aug 10, 1998	Aug 17, 1998	204.2
	RA-1	Sep 21, 1998	Oct 01, 1998	248.6
	LA-1	Oct 07, 1998	Oct 15, 1998	<u>252.1</u>
Total HQ Diamond Drill Footage				908.2
LA = left abutment drill hole LC = left channel drill hole RC = right channel drill hole RA = right abutment drill hole AUG = auger hole				DHPP = drill hole power plant DHS = drill hole spillway DHT = drill hole tunnel SSD = sites saddle dams

Exploration Techniques

An all-terrain CME-850 track-mounted drill rig was used to drill HQ diamond drill holes and auger 6-inch flight auger holes at five of the six sites explored. Holes were normally drilled about two-thirds of the way up each abutment, and one hole was drilled on each side of the channel. Angle holes were drilled in lieu of vertical holes when it was possible to intersect mapped faults to verify their presence and obtain data about the faults' thickness, orientation, gouge,

fracturing, and permeability. Piezometers constructed of slotted 2-inch PVC pipe were set to 60 feet below ground surface in each drill hole.

Periodic water level measurements are being made to record the depth to groundwater. Each hole was capped with a lockable steel monument set in concrete.

Augering was done to determine the depths to bedrock, water levels, and soil characteristics.

Water pressure testing consisted of double packer tests ranging in length from 10.9 feet to 13.1 feet, along with holding tests to determine the permeability of the foundation bedrock. A total of 189 double packer tests were performed in the 20 diamond core holes drilled.

Preliminary grouting requirements for the six sites explored at the projects were estimated by calculating permeability values as outlined by USBR (DOI 1973). Modified Lugeon values were also calculated as outlined by Houlsby (1976). A full review of both permeability and Lugeon calculations is presented in Technical Memorandum B, which is on file at DWR's Northern District office.

Diamond drill core documentation consists of 8-1/2" by 11" photographs, close-ups of special features, and drill logs. These are presented in Technical Memorandum A, on file at DWR's Northern District office.

Conclusions and Recommendations

Tables 2, 5, 10, and 15 summarize the foundation conditions for the four sites drilled in the Sites Reservoir Project. Tables 18 and 21 summarize foundation conditions at the Hunters and Logan Dam sites in the Colusa Reservoir Project. Technical Memorandum A provides drill core photographs and logs for the 36 holes drilled and augered. Technical Memorandum B documents and analyzes the water pressure testing. Technical Memorandum C provides details of the construction of piezometers and hydrographs from monitoring of groundwater levels. These technical memoranda are published separately.

We conclude that the foundations drilled appear to be suitable for the proposed structures. Other conclusions follow:

- No evidence of Quaternary fault movement has been found at any of the dam sites investigated by the consulting firm of William Lettis and Associates as part of an ongoing fault and seismic investigation.
- In addition to the mapped fault traces, drill core data indicate that other minor faults and shears exist. The mapped fault traces and the minor faults and shears should not pose any unusual construction difficulties.

- The average permeability for all the holes tested is 0.12 feet per day. In general, sandstone has the highest average permeability at 0.18 feet per day, followed by mudstone at 0.15 feet per day, and then conglomerate which has the lowest permeability at 0.02 feet per day. Overall, the rocks have little primary permeability. Instead, zones of high water take are associated with the development of secondary permeability through weathering, extensive fractures, or jointing. This is most common in the sandstone, which has regular and pervasive jointing and fracturing. Where intersected by drilling, the faults are mostly impervious; however, associated zones of fracturing may exhibit local increases in permeability.
- There should not be any significant problems with grouting the foundations evaluated; however, additional exploration should be done prior to construction. This is especially true in the right abutment of the Golden Gate Dam site where an unexpectedly high permeability at depth is probably related to jointing in the sandstone. There may also be some random fracturing in the foundation as the toe of this slope has previously been blasted and quarried.
- The rock strengths should be adequate for the dam foundations as proposed. Drill core samples have been collected and forwarded to DWR's Bryte Chemical Laboratory from the Sites, Golden Gate, and Hunters Dam sites, along with sandstone samples from Sites Quarry. Only the quarry and Hunters Dam site samples have been tested at this time. Three moderately weathered sandstone samples from the quarry averaged an unconfined compressive strength (UCS) of 4,998 pounds per square inch (psi) when dry and 3,589 psi when wet. Three fresh sandstone samples from the quarry had a UCS of 9,568 psi when dry and 6,983 psi when wet.

Additional subsurface exploration is recommended at the Sites and Colusa Reservoir Projects. At the Sites Project, DWR's Northern District Geology Section recommends the following:

- The possibility that the Salt Lake fault or associated deformation exists in the vicinity of Sites Dam site needs to be further evaluated. Additional mapping and drilling will be required. This should be done in conjunction with the ongoing Phase II Fault and Seismic Investigation being conducted by William Lettis and Associates.
- Seismic refraction surveys should be done on terrace deposits in the channel to further define the depth to bedrock and the seismic velocities for rippability of the foundation bedrock.
- Additional drill holes should be drilled at the Golden Gate outlet works, especially deep holes near the top of the sandstone ridges to evaluate maximum cover and rock conditions for tunneling operations and groundwater inflow to the tunnel. Additional holes need to be drilled at the top of the proposed

spillway locations to determine foundation conditions. One hole should be placed at the gateworks and drilled at least 400 feet to intersect the tunnel invert. This will probably require a helicopter skid rig because of the steep topography. Seismic refraction surveys should be performed on terrace deposits at the western inlet works and the eastern outlet works to further clarify depth to bedrock as well as seismic velocities for rippability estimates of the foundation bedrock.

- Several more drill holes should be placed along the northern saddle dam alignment ridge where the Salt Lake fault and the associated northeast-trending tear faults intersect it. Several of these may also require a helicopter skid rig. Seismic refraction surveys should be done at each of the saddle dams, especially where there has been no drilling. This should further clarify depths to bedrock, as well as seismic velocities and rippability.
- The downstream curved alignment and/or either of the straight upstream alignments at the Golden Gate Dam site may need to be drilled. The Northern District is coordinating with DWR's Division of Engineering on this decision.
- Additional exploration will be required along the canal alignment between the Sacramento River and the forebay.

At the Colusa Reservoir Project DWR's Northern District Geology Section recommends the following:

- Two angle holes should be drilled at the Hunters component of Hunters Dam site. One hole should intersect the lineament mapped across the ridge just south of the Hunters water gap, the other angle hole to cross-drill the channel itself. This strategy should also be followed at the Prohibition component. This will mean a total of four angle holes recommended for the Hunters Dam site.
- The northern Colusa Reservoir saddle dams need to be mapped to evaluate any drilling and/or trenching requirements, especially where the Salt Lake fault may intersect the proposed alignment.
- The depths to competent foundation rock for each site have been estimated by drilling, water pressure testing, and some seismic refraction surveys. The location and orientation of faults are based on a few channel exposures and foundation drilling. Prior to construction, major mapped faults need to be further delineated by diamond core drilling or trenching. A test-grouting program should also be performed at each of the major sites with emphasis on directional drilling across the prominent joint sets and logged zones of fracturing.

Regional Geology

The project area is located in the northwestern part of the Sacramento Valley on Cretaceous sedimentary rocks and Tertiary sedimentary deposits at the contact between the Great Valley and Coast Ranges geomorphic provinces (Figure 3). The Cretaceous sedimentary rocks are a thick sequence of marine sedimentary deposits that have been uplifted and eroded to form a series of north-trending ridges. The four main dam sites of the Sites and Colusa Reservoir Projects lie roughly in line along one of these ridges (Figure 2). Plio-Pleistocene deposits of the fluvial Tehama Formation cap some of these ridges. Quaternary terrace deposits, Holocene alluvium, colluvium, and landslide deposits are present in and along the stream channels and hillsides.

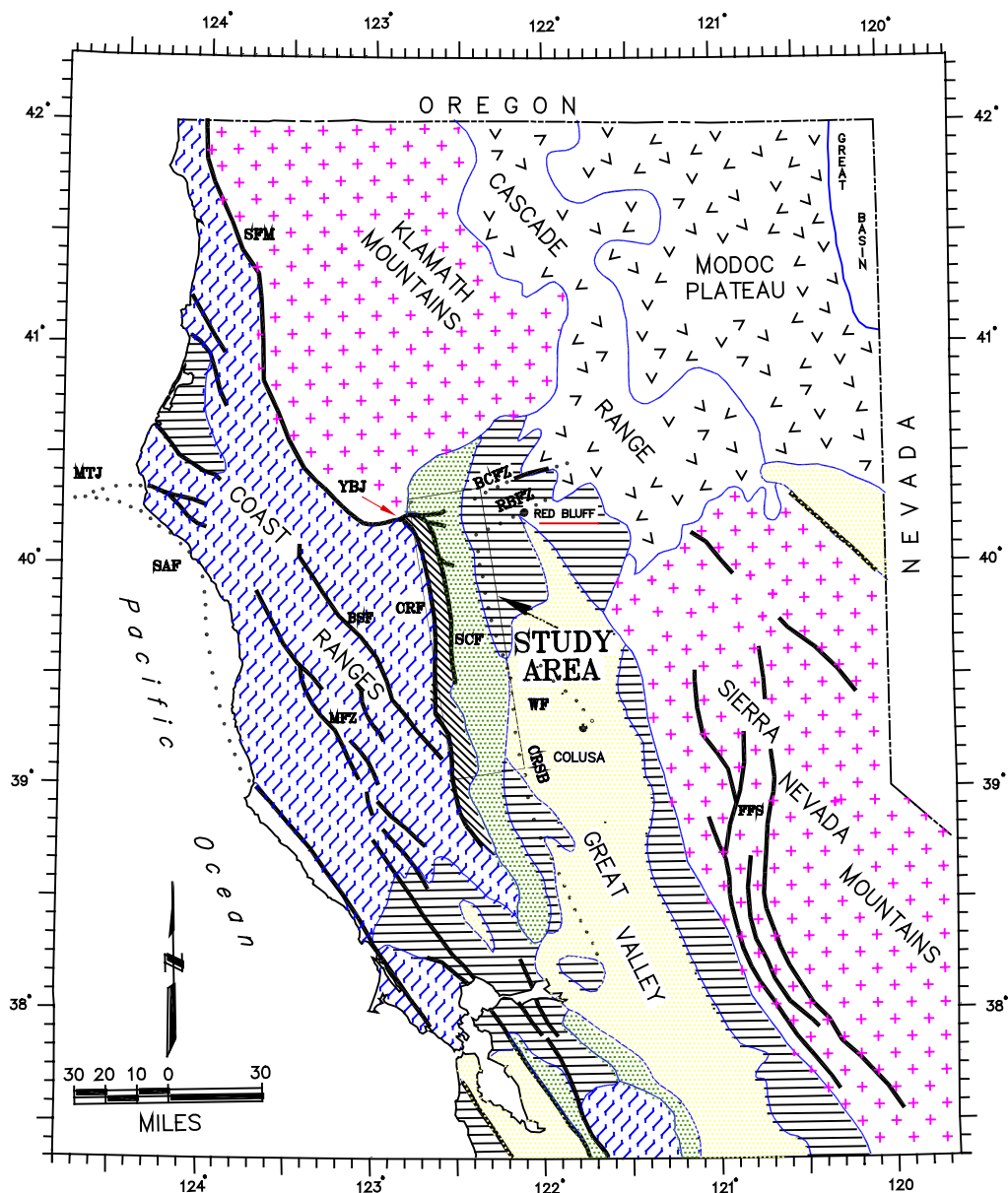
West of the dam sites, the proposed reservoirs and their drainage areas extend into the Coast Ranges geomorphic province.

Coast Ranges Geomorphic Province

The Coast Ranges extends for 600 miles in a northwesterly direction from the Transverse Ranges in Southern California to north of the California-Oregon border. They are complex and consist of many types of rocks ranging in age from Jurassic to Tertiary. Here graywacke, metagraywacke, shale, argillite, chert, limestone, and mafic, and ultramafic rocks have been intermingled by pervasive shearing and the formation of melanges. These rocks are part of the Franciscan complex, which represents the basement rocks of the Coast Ranges in the project area. Low- and high-grade metamorphic rocks may occur with unmetamorphosed sedimentary rocks in a single outcrop. The general structural trend is northwest.

At several localities in the Coast Ranges, Upper Jurassic beds pass gradationally downward into pillow lavas and pillow breccias that form the upper horizons of an ophiolite sequence (Bailey et al. 1970). This Coast Range ophiolite is believed to represent pieces of oceanic crust and upper mantle that was severely dismembered and structurally dislocated when it was accreted onto the western margin of North America. It consists of sheared serpentinite and small blocks of metamorphosed and sheared gabbro and diabase. These blocks are considered to be fragments of oceanic crust and upper mantle contemporaneous to the Franciscan complex and Great Valley sequence. Radiometric dates on gabbroic rocks indicate that the igneous rocks of the ophiolite are Late Jurassic in age (Lanphere 1971), the same age as the lower part of the GVS. In most places it has been severely dismembered and structurally dislocated in part by underthrusting of the Franciscan Complex during the Mesozoic, and in part by reverse-faulting in the steep limbs of much younger Tertiary folds (Raymond 1973). It crops out along the base of the GVS about 10 miles west of the dam sites and is almost entirely faulted out along the Coast Range thrust. It also continues at depth beneath the reservoir area.

FIGURE 3



GEOLOGIC UNITS

	Quaternary Sedimentary Deposits		Upper Jurassic/Cretaceous Sedimentary Rocks of the Coast Ranges
	Quaternary and Tertiary Volcanic Rocks of the Cascade Range and Modoc Plateau.		Upper Jurassic to Cretaceous Mafic to Ultramafic Rocks
	Tertiary Sedimentary Deposits		Mesozoic - Paleozoic Metamorphic and Granitic Rocks of the Klamath and Sierra Nevada Mountains.
	Upper Jurassic/Cretaceous Sedimentary Rocks of the Great Valley		Geologic Contact
			Fault-- Dotted where Concealed

FAULTS

SAF	San Andreas Fault	YBJ	Yolla Bolly Junction
CRF	Coast Range Fault	RBFS	Red Bluff Fault Zone
SPM	South Fork Mountain Fault	CRSB	Coast Range-Sierran Block Boundary
SCF	Stony Creek Fault	WF	Willows Fault
BCFZ	Battle Creek Fault Zone	MTJ	Mendocino Triple Junction
MFZ	Maacama Fault Zone	BSF	Bartlett Springs Fault
FFS	Foothills Fault System		

STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

REGIONAL GEOLOGIC MAP OF NORTHERN CALIFORNIA

Great Valley Geomorphic Province

The Great Valley Geomorphic Province is a nearly flat alluvial plain extending from the Tehachapi Mountains in the south to the Klamath Mountains in the north; to the Sierra Nevada in the east and the Coast Ranges in the west. This large elongate northwest-trending asymmetric structural trough has been filled with a tremendously thick accumulation of sediments eroded from the adjacent ancestral Sierra Nevada and Klamath Mountains ranges from the Jurassic to the Present. It has a long stable eastern shelf supported by the subsurface continuation of the granitic Sierran slope and a short western flank expressed by the upturned edges of the basin sediments. The western edge has eroded to form a series of northwest-trending, eastward-dipping ridges of sandstone and conglomerate separated by valleys underlain by siltstone and mudstone. Easterly erosion through these sandstone ridges has formed water gaps on which the proposed dams are sited. In the project area, the geomorphic province includes Upper Jurassic to Cretaceous marine sedimentary rocks of the Great Valley sequence; fluvial deposits of the Tehama Formation; terrace and stream deposits of the Red Bluff, Riverbank, and Modesto Formations; and older and younger Quaternary sedimentary deposits.

Great Valley Sequence

All of the proposed structures are sited on rocks of the Great Valley sequence. This sequence is one of the thickest and most complete Upper Mesozoic sections in North America. The section consists principally of clastic sedimentary rocks that occur in simple stratigraphic order, are folded and faulted locally but are not disrupted in detail, and are not affected by other than mild metamorphism.

The GVS and the Franciscan complex are the same age. The structural position of the GVS above the Franciscan complex results from regional overthrusting. The Coast Ranges represent a variety of ocean floor and trough deposits dragged downward against, and added to, the continental margin by plate subduction. In mid-Tertiary time, subduction of the oceanic plate and this accretion of Coast Range materials ceased and right lateral faulting along the San Andreas fault began. More recently, as underthrusting along the trough ceased, geologically rapid uplift occurred (Silver 1971; Calif., Sacramento Valley 1978). Since then, nonmarine deposition occurred in the Sacramento Valley (Hackel 1966), indicating that the basin had been uplifted above sea level.

The thrust fault contact between the Coast Ranges and the GVS marks the former position of a subduction zone, and the Sierra Nevada batholith about 100 miles east of the project area represents the eroded plutonic base of a volcanic arc that stood landward of the trough. Some of the sedimentary material of the GVS was eroded from the volcanic arc and deposited as deep marine turbidites in a large elongate northwest-trending structural trough. This trough was floored with basaltic and ultramafic oceanic crust (Coast Range ophiolite). The sediment sources

for the turbidites are thought to have been the Sierra Nevada batholith to the east and the Klamath Mountains to the north. Locally the turbidites include materials derived from the underlying oceanic crust.

These turbidites were deposited by gravity flow mechanisms at different times and places along the margins of the trough. These deposits are, therefore, lenticular, fan-, or tongue-shaped units set in a continuum of fine-grained deposits. The individual sandstone and pebble conglomerate beds wedge out or grade into finer-grained material over distances of less than one-half mile, or as much as 40 miles (Ingersoll et al 1977), and probably represent distributary channels in the mid-fan and outer fan environment of submarine valleys.

Turbidite lithologies consist of interbedded sedimentary rocks dominated by mudstone and siltstone, interlayered with thin to thick sequences of sandstone and conglomerate. All three rock types were deposited sub-horizontally to horizontally and have been tilted to the east by thrust faulting during the Tertiary, with a roughly north-south trending strike. This tilting causes the topography in the area to be dominated by ridges of sandstone and conglomerate. The mudstone is more easily weathered and is, therefore, not a prominent ridge-former. In nearly all cases, the ridges pinch out along strike, unless disrupted by faults or other structural phenomena.

The Sites and Golden Gate Dam sites are located on the eastern flank of the ridge near the contact between the Cretaceous Cortina Formation and the underlying siltstones and mudstones of the Cretaceous Boxer Formation. This contact is generally taken to be the lowest major sandstone unit.

The Boxer Formation consists of thin bedded mudstones with scattered thin to medium sandstone interbeds representative of basin-plain deposits of distal turbidites (Ingersoll and others 1977). The base includes the Salt Creek Conglomerate Member. The Boxer Formation is less resistant to weathering and erosion.

The Cortina Formation consists of a greater proportion of sandstone, with moderate to thick mudstone interlayers. The basal member of the Cortina Formation is the Venado sandstone (Photo 1). Near the base, the sandstone is primarily fine- to medium-grained and hard, and it occurs chiefly in 1- to 10-foot thick beds. Petrographic studies indicate that the rock is cemented by carbonates and by a silica-clay matrix. The Venado includes a lesser amount of well indurated, crudely fissile mudstone that occurs as 1/8- to 6-inch beds. Mudstone constitutes about 5 percent of the basal Venado.

Above the basal unit, mudstone beds increase to nearly 50 percent of the section. Further up the section, the Venado consists of repetitive intervals of medium to thick bedded sandstone and thinner bedded sandstone with about an equal amount of mudstone (DOI-USBR 1969). The bedded sandstone forms the eastern ridge that is the proposed location of the Golden Gate Dam.



Photo 1. Typical exposure of Venado Sandstone in the Project Area

The mudstones of the Yolo Shale Member are laminated to thin-bedded, range from 800 to 1,000 feet thick and occupy the strike valleys between the Venado and Sites sandstone members.

Exposures of the Sites sandstone are located within 15 miles south of the reservoir area and consist of 1,500 to 2,000 feet of interbedded sandstone and siltstone. This sandstone member wedges out into a thick mudstone sequence about 8 miles south of the southern edge of the reservoir boundary.

The mudstones in the project area are typically dark gray to black, and thinly laminated, and they have closely spaced and pervasive joints. When fresh, the mudstones are hard, but exposed units weather and slake readily. The mudstones underlie the valleys and some west-facing ridges because of the minimal resistance to weathering and erosion.

The sandstones are mostly light green to gray. They are considered to be graywackes in some places because of the percentage of fine-grained interstitial material. The sandstone beds range from thinly laminated to massive. In many places, they are interlayered with beds of conglomerates, siltstones, and mudstones. Massive sandstones are indurated and hard with widely spaced joints, forming the backbone of most of the ridges. The interbedded conglomerates consist of lenticular and discontinuous beds that vary in thickness from several feet to more than 100 feet. These conglomerates, cemented and very hard, are similar to the sandstone in hardness and jointing. Clasts in the conglomerate range in size from

pebbles to boulders but are mostly gravel-sized. They are composed primarily of cherty volcanic rocks, granitic rocks, and sandstones set in a matrix of cemented sand and clay. In Colusa County, a persistent conglomerate, the Salt Creek Conglomerate, marks the base of the Upper Cretaceous. Similar though discontinuous conglomerates are found more or less at the same stratigraphic level at the north end of the valley. These conglomerates contain reworked Lower Cretaceous clasts, which may indicate a period of local uplift and erosion at the end of the Lower Cretaceous.

Tertiary Sedimentary Deposits

Tertiary and Quaternary fluvial sedimentary deposits unconformably overlie the Great Valley sequence. In the study area, these belong to the Plio-Pleistocene Tehama Formation. Thin, discontinuous, and deeply weathered fluvial fan deposits were derived from the erosion of the Coast Ranges and Klamath Mountains. Eastward, the deposits thicken and coalesce, forming a broad, thick fluvial outwash plain that contains pale green to tan semiconsolidated sand, tuffaceous sand, and silt with lenses of gravel. The Nomlaki Tuff Member occurs near the bottom of the Tehama Formation and has been age-dated at about 3.3 million years. It consists of white, tan, or pink dacite pumice tuff and lapilli tuff that is about 30 feet thick along the west side of the valley. Most of the tuff is believed to have been deposited as an ash fall from a major volcanic eruption.

In places east of the project area, the distinctively red clayey gravel of the Red Bluff Formation caps the Tehama Formation. The Red Bluff remnants represent an extensive Pleistocene peneplain that once covered much of the northern Sacramento Valley.

Quaternary Sedimentary Deposits

Erosion of the Great Valley sequence rocks has deposited sediments Holocene to mid-Pleistocene in age. These deposits include stream terraces, floodplain sediments of clay and silt, colluvium and landslides, and active stream channel deposits of sand and gravel. Helley and Harwood mapped these units in detail in the project area in 1985 (Calif., Sacramento Valley 1985).

Stream terraces form flat benches adjacent to and above the active stream channel. Up to nine different stream terrace levels have been identified in the project area. Terrace deposits consist of several to 10 feet or more of clay, silt, and sand overlying a basal layer of coarser alluvium containing sand, gravel, cobbles and boulders. USGS has given four terrace levels formational names. These are the Upper Modesto, Lower Modesto, Upper Riverbank, and the Lower Riverbank Formations. These formations range in age from 10,000 to several hundred thousand years old.

The Modesto Formation consists of the lowest distinct alluvial terraces lying topographically above the Holocene stream deposits. The Modesto includes tan and light gray gravelly sand, silt, and clay. The upper member is unconsolidated and unweathered, and it forms the topographically lowest terraces only a few meters thick over older alluvial deposits. The surface preserves the original fluvial morphology with relief of 1 to 2 meters. The soils on the upper member have A/C horizons but lack an argillic B horizon. The lower member can be slightly weathered and forms terraces that are topographically higher than the upper member. The surface morphology is smooth and more extensive than the upper member. The soils on the lower member contain an argillic B horizon with an increase in clay content and red color.

The Riverbank Formation consists of weathered reddish gravel, sand, and silt. It is differentiated from the younger Modesto by its terraces being topographically higher and by its more developed soil profile. The upper member is unconsolidated but compact dark brown to red alluvium and forms the lower of the Riverbank terraces by about 3 meters but can be up to 5 meters above the lower Modesto terrace. The lower member is a red semi-consolidated gravel, sand, and silt. Its surface is higher and more dissected than the upper member and has a stronger soil profile.

Alluvium consists of clay, silt, sand, gravel, cobbles, and boulders found in present stream channels and clay, silt, and sand found on floodplains. Quaternary alluvium is loose sedimentary deposits of soil, rock, clay, silt, sand, gravel, and boulders.

Colluvium, or slope wash, occurs at the face and base of a hill. It consists mostly of soil, but contains a sizable fraction of angular rock fragments and some organic material.

Landslide deposits are similar but more defined and generally deeper than colluvium. Landslides occur along the reservoir rim or steep west-facing ridges but are generally small, shallow debris or earth slides or debris flows, and may be common along fault traces. These could be unstable in the event of a rapid drawdown of the reservoir. Rock fall deposits also occur, especially on the back side of dip slope sandstone ridges and in water gaps.

Regional Structure

The proposed reservoirs and dam sites have moderate topographic relief with ridge to stream channel elevation changes of about 500 feet. The geologic structure is readily reflected in the topographic expression of the region. Areas underlain by bedrock units consist of parallel northerly trending ridges and valleys, while overlying sedimentary deposits have formed an intricate dendritic drainage pattern. Major structural features include faults, folds, and joints.

Regional Faulting

In general, south of Red Bluff, regional faults strike to the northwest, roughly parallel to the San Andreas fault. Most of the fault plane solutions for the Sacramento Valley and Coast Ranges in this area show right lateral movement. However, faulting along the Coast Ranges-Sierran Block boundary also has a large component of east-west thrusting.

Numerous smaller faults trend askew to the regional faults and the regional structural trend. These are called cross, tear, or transverse faults. Most of the dam sites and saddle dam sites have these faults traversing through or near the proposed dam foundations. They are believed to be Late Cretaceous in age and evidence has yet to be determined if faults demonstrate any Quaternary movement.

The faults represent potential areas of weakness in the foundation. Typically, faults require treatment, such as overexcavation and backfilling with concrete. Faults are potential seepage corridors and may require additional grouting. Because of the inherent weakness of faults, landslides are commonly associated with fault surface traces.

Salt Lake Fault, Sites Anticline, and Fruto Syncline

The Sites anticline is associated with the adjacent Fruto syncline. It extends about 45 miles from near the town of Sites north to near the town of Newville. The anticline is a tight fold with steeply dipping and locally overturned strata on both limbs. Based on analysis of seismic reflection data, William Lettis & Associates (1997) interprets the anticline as a fault-propagation fold developed above one or more blind thrust faults. The Salt Lake fault is a high-angle thrust fault that developed adjacent to the axis of the doubly plunging Sites anticline (DWR 1978). Salt water springs and gas seeps occur along the fault trace. In several locations the fault is concealed by unbroken Pliocene Tehama Formation, suggesting that the latest movement occurred prior to this time.

Based on the work done by the Working Group on Northern California Earthquake Potential (USGS 1996), it is probable that the Salt Lake fault, the Sites

anticline, and the Fruto syncline are features related to the Great Valley fault. The fault trends mostly north-south and is located about 1 mile west of the Thomes-Newville, Sites, and Colusa Project dam sites. The Sites anticline (Kirby 1943) and the Fruto syncline (Chuber 1961) are flexure structures extending northwest from the general area of Sites to about 40 miles north to Newville, and possibly as far as Paskenta. It is generally believed that the folds and associated faulting--Salt Lake fault and numerous transverse faults--in the Middle Cretaceous sediments were formed as a result of east-west compression prior to Pliocene (Tehama Formation) deposition (Chuber 1961). It is now, however, considered possible that some deformation along this zone may be associated with deep thrusting along the Coast Ranges-Sierran Block boundary zone.

Field inspections by DWR and WLA of these three features suggest that the zone is complex, with numerous smaller folds, faults, and shears along a wide area of deformation. Exposures in Sites, Funks, and Logan Creeks may be expressions of this deformation.

There also appears to be a bedding, dip, and strike discontinuity between the Middle and Early Cretaceous sedimentary rocks. Exposures are poor, and more work needs to be done in the area to determine the true character of this zone.

William Lettis & Associates (1997) surveyed three geomorphic fluvial terrace profiles across the Sites anticline. They found no evidence for systematic uplift or tilting evident on surfaces dating back at least to the last 30,000 years. The Sites anticline also lacks the pronounced geomorphic expression similar to the Dunnigan Hills and the Rumsey Hills, two actively forming anticlines in the southwestern Sacramento Valley.

William Lettis & Associates also performed aerial and field reconnaissance of the Salt Lake fault. They observed undisturbed colluvium overlying the fault trace at numerous locations. Quaternary terraces overlying the fault appear to be undisturbed.

Coast Range Fault

The Coast Range thrust is a curvilinear fault that trends northwest in the northern portion of the fault and trends south on the southern portion of the fault. The fault is about 10 miles west of the dam sites and is defined to be at the contact between the Franciscan complex on the west and the Coast Range ophiolite on the east. Thrusting occurred during Late Jurassic time and has probably not occurred since then. The fault generally dips steeply. It is one of the longer faults in the state, extending from south of Colusa Reservoir to near the Oregon border. There is general agreement that the fault originated in the Cretaceous as a result of east-dipping subduction. However, there is little agreement about the fault's current activity and recent displacement history.

At the surface, it appears to be a high-angle, west-side-up reverse fault. However, recent research suggests that it probably has over time moved under compression, extension, and right lateral strike slip (Jayko 1987; Wentworth et al. 1984; Platt 1986; Krueger and Jones 1989).

Phipps and Unruh (1992) believe the fault has been a subduction fault that has locally been reactivated as a thrust and possibly a normal fault. They also believe the fault to be allocthonous, that is, separated from its deep-seated roots. The fault has been cut and folded by later thrusts and by strike-slip faults. This fault is generally considered a Mesozoic and early Tertiary feature. A part of the fault northwest of Lake Berryessa shows evidence of Quaternary displacement. It is uncertain if the Coast Range fault is presently active. Near the Red Bank Project, Harlan Miller and Tait (1983) found no evidence of movement since the deposition of the Nomlaki tuff 3.3 million years ago.

Stony Creek Fault

The Stony Creek fault is east of and runs parallel to the Coast Range fault. It is also the contact that separates the Coast Range ophiolite from the Great Valley sequence to the east. This contact is believed to be both depositional and faulted, showing both normal and reverse movement. In most places, the fault is near-vertical. This fault is only of concern because of its proximity to the proposed structures.

Past investigations (ESA 1980; DWR 1982; WPRS 1981) studying movement along this fault have been inconclusive. Evidence from these studies suggests that at least some of the segments have been inactive for at least the last 130,000 years, but most likely the last 250,000 years.

Outcrops of the fault trace along roadcuts near Grindstone Creek indicate that the contact is sharp and well defined, suggesting that not much movement has occurred. USGS (1996) does not consider it a potential source of magnitude 6+ earthquakes.

Corning and Willows Faults

The Corning fault is not expressed at the surface but is based on well data and the overlying deformation, including the Corning domes and the Greenwood anticline. Pleistocene deformation and the association of microearthquakes suggest that the fault may be an active steeply east-dipping reverse fault (Wong et al. 1988). Near its southern end, the Corning fault is interpreted to trend NW-SE and either splay off from or terminate against the Willows fault (Harwood and Helley 1987).

The closest approach of the Willows fault to any of the dam sites is 12 miles from the Sites Dam site. The Willows fault appears to be a steeply dipping reverse

fault with the east side up. It is probably the most extensive fault within the valley and appears to be a major tectonic boundary dividing the Sacramento Valley into two late-Cenozoic structural provinces. North of Willows, the fault changes to a northwest strike and appears to splay into the Paskenta, Cold Fork, and Elder Creek faults (Wong et al. 1988).

Regional Folding

Regional folds generally trend in the same northwest direction as the regional faults. Some of the folds such as the Corning and Dunnigan Hills are probably the surface expression of deeper movement along faults. Regional folding is consistent with a compressive stress regime oriented about N75°E.

The largest structure is the synclinal folding of the Sacramento Valley. On the west side, the Cretaceous mudstone, sandstone, and conglomerate dip moderately to steeply east and strike northwest. On the east side, similar beds dip to the west and strike in about the same direction.

The Chico monocline occurs along the east side of the valley between Chico and Red Bluff. Along the east side, beds dip shallowly to the west; but at the axis of the monocline, the beds dip more steeply toward the center of the valley. The axis is also displaced by numerous faults trending parallel to the axial plane.

Regional Jointing

Jointing is pervasive and exhibits a similar regional orientation. It is usually not present in rocks younger than the Cretaceous. The Cretaceous mudstones are generally the most jointed with spacings common from less than an inch to a foot. Joint directions are perpendicular to each other with one set parallel to the bedding and the other two sets perpendicular to the bedding and each other. This pervasive jointing contributes to slaking of the exposed mudstone outcrops.

The Cretaceous sandstones and conglomerates vary in joint spacing depending mostly on the thickness of the individual beds. Joint directions are similar to the mudstones. The massive units have joint spacings ranging from a few feet to several tens of feet or more.

Three general joint sets exist in the area of the projects. The dominant one strikes mostly east-west and dips steeply to the north and south. Two other secondary sets strike roughly east-west, one dipping in a broad range to the NE and another dipping to the SW. Intersection of one of the two dominant joint sets with the relatively minor one produces characteristic "V" notches in the more resistant thin sandstone layers.

Regional Seismicity

The seismicity of the western Sacramento Valley foothills has been recorded by a number of different agencies over the last 100 years. These agencies include the University of California, Berkeley; the California Department of Conservation; the U.S. Geological Survey; and the California Department of Water Resources. The accuracy in the measurement of the epicenters, focii, and the magnitude has improved over the years as more instruments with greater sensitivity and accuracy have been installed. The older data were recorded with instruments located several hundred miles away. Consequently, the plotted locations of seismic events may be off by tens of miles.

Earthquakes as small as magnitude 1 and magnitude 2 have been recorded in the project area since the installation of the Northern California Seismic Network beginning in 1975 (Technical Memorandum A). The memorandum also includes an analysis of the earthquake activity to date. In 1991 DWR, as part of the Red Bank Project investigation, worked with USGS to install four additional seismic stations in the area. Plotting epicenters with these data can be accurate to within several miles for relatively small earthquakes occurring close by. USGS provided DWR with an analysis of the data recorded to date by the network.

According to USGS, the number of earthquakes recorded by the network is typically three or fewer and often zero per month.

Historic Earthquakes

Historic seismic activity for the last 200 years or so in the central and northern part of the Sacramento Valley has been low to moderate compared to other areas of California. Events in northern California larger than magnitude 6 have occurred in the San Francisco Bay region, near Eureka, north of Tahoe, and the Vacaville-Winters area. Events larger than magnitude occurred near Eureka in 1923 and 1992 and in the San Francisco area in 1868, 1906, and 1989.

Major fault zones known to be seismically active near the project area include the Foothills fault system; Chico monocline; blind thrusts of the Great Valley fault; the Willows and Corning faults; the Bartlett Springs, Maacama, and San Andreas faults; and the Cascadia subduction zone.

The Winters-Vacaville earthquakes of April 19 and 21, 1892, are the two earthquakes with the most significant impact on the design of the proposed projects, particularly Thomes-Newville, Sites, and Colusa. This is because the proposed dams and structures are overlying the same Great Valley fault (Coast Ranges-Sierran block boundary) that is believed to have been the cause of the earthquakes. This zone is believed to extend the entire length of the Great Valley.

The two major Winters-Vacaville temblors and numerous aftershocks produced widespread damage throughout much of Solano, Yolo, and Napa Counties. The towns of Winters, Vacaville, and Dixon suffered massive destruction with Modified Mercalli intensities reaching IX and estimated magnitudes of 6.0 and 7.0 (Wong et al. 1988). A similar temblor (magnitude 6.7) to these earthquakes occurred in 1983, causing considerable damage in the Coalinga area. Another temblor (magnitude 6.1) occurred in 1985 in the Kettleman Hills.

On January 7, 1881, an estimated magnitude 5 occurred east of Red Bluff at the edge of the Cascade Range. On June 6, 1884, an estimated magnitude 5 occurred near or north of Red Bluff. One wall cracked. A magnitude 4.5 occurred in the Willows area on July 24, 1903, resulting in some cracking and falling plaster. An event of Modified Mercalli intensity VI occurred on April 16, 1904, south of Redding. A magnitude 5.7 occurred northeast of Chico on February 8, 1940, and a magnitude 4.6 near Chico in 1966. Both of these were probably associated with the Chico monocline. A magnitude 4.7 event occurred on April 29, 1968, near Willows (Wong et al. 1988).

On August 1, 1975, a magnitude 5.7 occurred near Oroville on the Cleveland Hills fault. This quake renewed interest in the Foothills fault system and speculations about reservoir-induced seismicity related to Lake Oroville.

Several earthquakes have occurred fairly recently near Redding, Chico, Cottonwood, and Willows. A series of earthquakes, including a magnitude 5.2 that occurred in November 1998, struck the Redding area over a period of months.